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The use of SARAL/AltiKa altimeter measurements for multi-site hydrodynamic model validation and rating curves estimation: an application to Brahmaputra River

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Abstract

Hydrodynamic (HD) modelling in data sparse region represents a challenge due to poor hydrological and topographic data availability. Recently, remote sensing techniques offer additional data that may help to improve the reliability and accuracy of such analysis. In this study, an attempt has been made to investigate the potential and added value of altimeter measurements for multi-site validation of the HD model and constructed rating curves (RCs) in a sparsely gauged Brahmaputra River, India. The HD model (MIKE 11) was developed for a Brahmaputra River stretch of 135 km, between Tezpur and Guwahati, where 4 ground-tracks of the SARAL/AltiKa (the first Ka band altimeter mission) cross the river. The Nash Sutcliffe efficiency (NSE) between HD model based water level and in-situ water level during calibration (January-October 2013) and validation (January-March 2014) was found to be 0.93 and 0.79 respectively. Calibrated and validated HD model was used to simulate water level and build rating curves at virtual stations. The bias correction (7.2 cm to 9.5 cm) was applied to the altimetry measurements before comparison with the modelled water levels. The root mean square error (RMSE) ranging between 15 cm to 42 cm was observed between the modelled and altimetry-derived water level at all the virtual stations, indicating the potential of satellite altimetry for multi-site validation of the HD model (inline with previous studies)

and validation of the constructed RCs. The availability of RCs at virtual stations allows the expansion of the gauging network along the Brahmaputra River, thus enabling the estimation of the discharge at additional locations and the potential evaluation of the contributions of lateral tributaries could be evaluated in future work.

Keywords: SARAL/AltiKa; satellite altimetry; hydrodynamic modelling; remote sensing; Brahmaputra River; rating curve

1 Introduction

Researchers dealing with flood hazard and risk assessment typically refer to available in-situ gauging stations for the calibration and validation of hydrological and hydrodynamic models. However, the numbers of gauging stations are decreasing since last decades (Vorosmarty et al., 2000) due to the high economical and temporal efforts required for their maintenance. The lack of gauging data such as stage-discharge relationship results in higher uncertainty in hydrological studies. Remote sensing techniques such as satellite altimetry are capable since long time to monitor continental water bodies at regular interval (Birkett et al., 2002). Various altimeter missions (e.g., past missions - ENVISAT, Topex/Poseidon and ERS2, current - Jason-3, SARAL/AltiKa and Senitnel-3) have shown there potential to monitor water levels (WL) of inland waterbodies (see e.g. Dubey et al., 2015, Santos et al., 2014, Papa et al., 2010;Birkett et al., 1998; Birkett et al., 1995). In particular, current SARAL/AltiKa mission with Ka-band allows high bandwidth of 480 MHz and provides vertical resolution of 0.3 m, which is better than previous Ku-band based altimeters having vertical resolution of 0.5m (Bonnefond et al. 2018).

HD models have been widely used for flood inundation mapping studies (Dhote et al., 2019; Mani et al., 2014; Horrit & Bates, 2001). Once the river geometry and roughness coefficients of the HD model are settled (prevailing uncertainties), perhaps after a calibration phase, the reliability of the modelling outcomes depends on the accuracy of the boundary conditions adopted by the model itself, which in turn typically depends on the availability of gauging data (see e.g. Domeneghetti et al., 2012). Extensive work has been done in combining remotely sensed data and HD models for flood inundation mapping and monitoring (Bhattacharya et al.,2019; Domeneghetti et al., 2014; Morales-Hernandez et al., 2013; Wright et al., 2008; Chatterjee et al., 2008), while less emphasis has been put on the use of remote sensing data for multi-site validation of HD model and construction of rating curves.

Domeneghetti et al., (2014) investigated the application of satellite altimetry data to calibrate the hydraulic model in a well gauged and surveyed river basin. They concluded that, for medium to large rivers, a model implemented by integrating satellite and in-situ data simulates the average streamflow condition better than one based on in-situ data only. Various studies in the literature report examples of calibration and validation of HD models carried using satellite altimetry (Chembolu et al., 2019; Jarihani et al., 2015; Yan et al., 2015; Neal et al., 2012).The first ever application of 2D HD model for central Amazon floodplain was validated using limited gauge observations and altimetry data (Wilson et al., 2007).In the case study of Brahmaputra River basin carried out by Schneider et al., (2017), the CryoSat-2 and Envisat altimetry data was used to calibrate the cross-sections extracted from freely available SRTM DEM to achieve best fit with the simulated water level. In case the temporal resolution of the water level retrieved using satellite altimetry is coarse, Michailovsky et al., (2013) suggested to combine river water levels at virtual gauging stations with the outcomes of a hydrological model (more specific-routing model) in a data assimilation framework. They formulated the routing model in terms of reach storage, which involves few assumptions such as trapezoidal cross-sections and measurement operator to estimate water stored in the reach using altimetry based water level as one of the input. Satellite altimetry data has been used for large scale hydrological-hydrodynamic modelling, such as streamflow forecast in the Amazon basin by assimilating in-situ and ENVISAT satellite data (Paiva et al., 2013) and estimation of average depth of the Ob river in Siberia using water level measurements from Topex/POSEIDON altimeter data (Biancamaria et al., 2009). All the discussed studies have either used satellite altimetry data independently or assimilated with the gauging data to calibrate and/or validate the HD and/or hydrological models.

The potential of satellite altimetry for flood forecast systems in transboundary river basins has been discussed by previous studies (Biancamaria et al., 2011; Hossain et al., 2014; Chang et al., 2019). Biancamaria et al. (2011) investigated the correlation between satellite altimetry measurements in the upstream part of the Brahmaputra River (Indian region) and in-situ measurements available downstream (Bangladesh) to forecast water elevation anomalies near Bangladesh border with lead time of 5 days. Attempts have been made to estimate daily river level/discharge using satellite altimetry data, such as altimetry observations in data assimilation framework (Tourian et al., 2017), ensemble learning regression (ELQ) using satellite altimetry data and a hydrologic model (Kim et al., 2019), and integration of altimeter samplings with macroscale hydrological model (Chang et al., 2019) for transboundary rivers.

Researchers have proposed to estimate discharge at ungauged sites using upstream in situ discharge data (Gianfagna et al., 2015,Birkinshauw et al., 2014,Tarpanelli et al., 2013, Emerson et al., 2005). The use of different altimeters (e.g., TOPEX-Poseidon, ERS-2, and ENVISAT) derived water level and in situ RCs to estimate discharge have demonstrated the advantage of using remote sensing data and in situ data for enhancing hydrological studies of a basin (Jasinski et al., 2001,Kouraev et al., 2005, Papa et al., 2010,Zakharova et al., 2006,Michailovsky et al., 2012,Birkinshaw et al., 2014). Also, hydrographs generated using rainfall–runoff models were combined with RCs to derive discharge using altimetry water level (Leon et al., 2006; Getirana et al., 2013). Paris et al., (2016) proposed a methodology for curve fitting between modelled discharge and altimetry water level to generate RCs in Amazon basin.

The classical stage-discharge power regression law built upon traditionally observed data has been used to generate RCs over decades for various basins all over the world (Herschy, 1993). The impact of change in flow section on RC can be taken into account in these methods using different fits. However, such methods does not consider various hydraulic factors while constructing the RC, such as change in roughness coefficient, change in downstream control and longitudinal water surface gradient (Di Baldassarre and Montanari, 2009). Another limitation of traditional RC is the extrapolation error, meaning the possible bias introduced when applying the RC for high flows, typically not covered during field measurements. Using HD modelling is an alternative to traditional methods to reduce both construction and extrapolation error of RCs based on few stage-discharge measurements, or the errors associated to hydraulic factors (Mansanarez et al., 2019; Domeneghetti et al., 2012, Lange et al., 2010). Having said that, to obtain consistent results (here RCs) at each river section using HD model, the spatial variability in the channel-floodplain requires careful calibration. Previous studies have shown how the validation of hydrological model with respect to the gauging data at the catchment outlet (single site validation) may not produce adequate results at other hydrometric stations (Bai et al., 2017; Nkiaka et al., 2017). Likewise, similar considerations are valid for the calibration of hydraulic models. Lang et al., 2010 validated the constructed RCs using limited available flood marks (water level). The availability of satellite altimetry data over a river for which HD model is available provides the opportunity for its multi-site validation, as well as the construction and validation of RCs at different locations.

Brahmaputra River is unique in terms of its channel-floodplain relation, transboundary in nature, flora and fauna and lateral bars and islands (Coleman 1969). Floods are recurrent events in Brahmaputra River, which result in loss of life and damage to property (Karmaker et al. 2010; Karmaker and Dutta, 2011). Every year people migrate during monsoon season from floodplain to safest place and come back again in post-monsoon. Thus, discharge measurement plays a vital role in flood management activities. During extreme flood events, direct measurement of discharge is very difficult due to practical constraints such as high flow velocities, partial or complete damage of gauging station. Therefore, exploration of RCs is a basic step for indirect estimation of discharge.

The present study demonstrates the significance of altimeter measurements over implemented HD model in sparsely gauged river stretch. The specific objectives are: (1) RCs construction using HD modelling at virtual stations; (2) the use of satellite altimetry data for multi-site validation of HD model and validation of RCs obtained by means of the numerical simulations. The HD model simulations produce RC at each cross-section. The reliability of the constructed RCs for sparsely gauged rivers cannot be tested if we do not have observations. In this case study, calibrated HD model using in-situ data and the availability of altimetry data enabled an option to verify the constructed RCs

In this study, we refer to water level retrieved over 4 tracks of SARAL/AltiKa 40Hz altimeter. HD model was settled for a river stretch of 135 km, from Tezpur to Guwahati, where 4 tracks of SARAL/AltiKa cross the river. The geographical and hydrological description of the study area and data used in the study are explained section 2. Section 3 outlines the methodology adopted to derive rating curves using HD model and retrieve water level using satellite altimetry data. Results corresponding to defined objectives are presented and discussed in section 4, while conclusions of the work are summarized in section 5.

2 Study area and data

The study area is a part of the Brahmaputra River Basin (BRB), as shown in Figure 1. The basin area (471,088 sq. km) shown in the Figure 1 is with respect to the outlet at Dhubri, Assam, India. However, BRB is a transboundary basin that spreads over a drainage area of 580,000 sq. km lying in China, Bhutan, India and Bangladesh (India-WRIS, 2016). Brahmaputra River originates in the Kailash ranges of Himalayas at an elevation of 5,150 m (just South of the lake called Konggyu Tsho) and flows for about 2900 km, 916 km on which in India. It consists of a network of multiple channels separated by small or sometimes temporary islands, which identify it as braided river. World’s highest average annual rainfall occurs in BRB at Cherrapunji-Mawphlang-Pynursla belt in the order of 11,000 mm. 85 % of the precipitation occurs during monsoon months, from May to October. The river is characterised by highly vulnerable islands, river banks, mobile beds and fine sedimentary environment. Every year the river runs with highest streamflow during monsoon season, from July to September, while low flow occurs during January to March. Average annual peak discharge value at Guwahati (Pandu) gauging station is 38,876 m^3/s (Dubey et al. 2015). 55.48 % of the basin is covered with forest and 5.79 % by water bodies (India-WRIS, 2016).Near real time mapping and monitoring of high flow events, drainage congestion and erosion are the major problems in the basin.

Figure 1. Overview of study area and modelled river reach

SARAL/AltiKa mission launched in February 2013, carries Ka band (35 Hz) altimeter and enhanced bandwidth (480 MHz). It is a joint venture between ISRO (Indian Space Research Organisation, India) and CNES (National Centre for Space Studies, France) and co-operation of scientists from both organisations allowing to explore potential of Ka band altimeter data. Primary objective of the mission is oceanography, climate and coastal region research studies while secondary is to monitor ice sheet, sea ice and inland water bodies (Bonnefond et al., 2018). In this study we used SARAL/AltiKa data (orbital repetivity – 35 days) of 04 tracks over Brahmaputra River for the period that goes from March 2013 to July 2016.Starting from July 2016 the satellite orbit has been changed to a drifting mode and thus it is no longer possible to have SARAL/AltiKa time series at the studied ground tracks (Bonnefond et al. 2018).

Daily in-situ water level and discharge series from January 2013 to May 2014 were procured from Inland Waterways Authority of India (IWAI) at two gauging stations (i.e. Tezpur and Guwahati). The surveyed river cross-sections of the Brahmaputra River at an interval of 2100 m (approximately) from Tezpur to Guwahati were also procured from the IWAI, Guwahati.

ALOS PALSAR Digital Elevation Model (DEM) with horizontal resolution of 12.5 m was downloaded from Alaska Satellite Facility (Dataset, 2017). ALOS PALSAR DEM (released in 2014) is a radiometrically terrain-corrected (RTC) product generated from Shuttle Radar Topography Mission (SRTM) GL1 data at 30 m resolution (Accuracy: Horizontal circular error at 90th percentile (CE90) 20 m; Vertical linear error at 90th percentile (LE90) 16m).

Land use land cover (LULC) map with 1:250000 scale was provided by Indian Space Research Organisation- International Geosphere Biosphere Programme (ISRO IGBP Programme: NRSC, 2006).

3 Methodology

The methodology adopted in the present study is illustrated in Figure 2. It consists of two major parts. The first part focuses on all the steps involved in setting up the HD model to simulate water level and rating curves at virtual stations falling within the modelled river reach. The second part deals with the water level retrieval using satellite altimetry data for multi-site validation of the HD model and validation of the rating curves. Details of each component are provided in following sub-sections.

Figure 2. Overall methodology adopted in the study

3.1 HD model setup to construct RCs at virtual stations

MIKE 11 HD model solving 1D Saint Venant Equations in fully dynamic mode has been used to simulate water level for a Brahmaputra river (DHI, 2014a). Freely available synthetic aperture radar based ALOS PALSAR DEM (Dataset, 2017) was used for hydro-processing in ArcGIS tool 10.1 to delineate river network and sub-basins of BRB (ESRI, 2012).

It can be seen from Figure 3 that four tracks of Saral/AltiKa (896, 165, 623, and 352) crosses the river between Tezpur and Guwahati. Points of intersection where altimeter ground-tracks cross the river channel are pointed out as virtual stations (Frappart et al. 2005, Leon et al. 2006).

There are 4 right bank tributaries (RT1, RT2, RT3, and RT4) and 01 left bank (LT1) tributary contributing to the main Brahmaputra River flowing from Tezpur to Guwahati. The HD model setup was done for the main Brahmaputra River (Tezpur to Guwahati), while contributions of the tributaries were considered as lateral inflows during simulation.

Figure 3. Brahmaputra River reach simulated with the HD model and SARAL/AltiKa tracks crossing the river

To increase the density of the river cross-sections so that curvature of the river is not comprised, additional cross-sections were extracted from the RTC product of the ALOS PALSAR (i.e., DEM at an interval of 500 m using MIKE HYDRO tool) (DHI, 2014b). Care was taken so that cross-sections were long enough to account for floodplain and channel. The floodplain topography can be well represented using spaceborne DEM, however, depicting bathymetry is quite difficult. Thus, nearest surveyed data was used to edit the DEM-based cross-sections to maintain the conveyance. Few extracted cross-sections not following the downslope topography from upstream to downstream were excluded. Finally, hybrid cross-sections were used in the HD model. The longitudinal profile of the main channel from Tezpur to Guwahati and the cross-section at 23000 m chainage is shown in Figure 4.

Figure 4. (a) Hybrid cross section at 23000 m chainage (b) Longitudinal profile of the main channel

Boundary conditions are needed to close the system of equations to be solved by the double sweep method (Abbot and Ionescu, 1967). Hydrometric data (water level/discharge) at all upstream boundaries and water level, discharge or relationship between water level and discharge (e.g. a rating curve) at the downstream boundary are required as boundary condition. In this study, a water level time series was imposed as boundary condition at upstream end (Tezpur), while rating curve is used at the downstream end (Guwahati). Contributions of tributaries were given in terms of discharge time series and considered in the model as point sources. Details of boundary conditions type are given Table 1. Hydrometric data acquired from IWAI was available only at the two gauging stations (i.e. Tezpur and Guwahati), while data for tributaries was estimated using drainage-area ratio method (Emerson et al. 2005). The drainage area ratio of the each tributary (Figure 3) was estimated by dividing the drainage area of respective tributary by the drainage area of BRB with outlet at Guwahati (414501.07 sq. km). The contribution of each tributary as lateral flow is given in Table 2.

Before setting up the boundary conditions configuration, we analysed the ratio of "difference between Guwahati and Tezpur discharges to the Guwahati discharge" in terms of percentage. It was found that the estimated ratio (i.e. the contribution of tributaries) was less than + 9 % for a period Jan-April 2013 and Nov-Dec 2013. High variation was observed for a period May-Oct, 2013 ranging from +10 % to – 30% (few points more than - 30%) indicating

Guwahati discharge less than Tezpur. The negative ratio may be due to the lateral propagation of the flood wave between Tezpur and Guwahati (being braided river; see Fig. 3) and error in rating curve used to estimate water level. The contribution of tributaries cannot be negative. However, the difference between water level time series was ranging from 17.5 to 20.5 m having good trend (R^2 = 0.65). Thus, we move ahead with water level time series as boundary condition for upstream end i.e. Tezpur. The contribution of tributaries (6.65 %) was estimated using drainage area ratio method considering discharge at Guwahati station only.

Table 1. Summary of boundary conditions

Table 2. Contribution of the tributaries

The Manning's roughness coefficient (n, $m^{-1/3}s$) is one of the most important parameter in HD modelling since it controls energy losses at every river station. For this study we built a lookup table that relates different LULC classes with n values. LULC classes were identified using ISRO IGBPLULC map and Google Earth high resolution imageries (Google Earth, 2018). Manning's n values were selected based on the literature and previous relevant studies (Bhattacharya et al 2019; Timbadiya1 et al 2015; Woldemichael et al. 2010; Chow 1959). The initial Manning's n values used for channel, settlement area, forest, agriculture area were 0.03, 0.2, 0.1 and 0.04 $m^{-1/3}$ s, respectively.

Finally, we referred to the calibrated and validated HD model (using in-situ data; explained in section 4.1) to generate water level time series and RC's at virtual stations.

3.2 Water level retrieval using satellite altimetry data

Satellite altimetry is a technique for measuring the height of a target surface. Altimetry measures the time interval between transmitted radar pulses from satellite antenna to the target surface and back to the satellite receiver. Combination of estimated time with the precise location of satellite gives height of the surface with respect to reference ellipsoid. Footprint of altimeter extends till several kilometres, thus creating multi-peak and complex waveform over large rivers, such as Brahmaputra, due to varying LULC, slopes and sand bars. These circumstances limit the application of the algorithms developed for waveforms over ocean. Saying that, return power received from water surface within altimeter footprint remains higher as compared to other features due to surface characteristics.

Virtual stations were identified based on SARAL/AltiKa tracks over Brahmaputra River. Focus was given to the tracks (896,165, 623, 352) passing over modelled river reach. Waveforms were extracted over virtual stations for 40 Hz waveform data of SARAL/AltiKa using Broadview Radar Altimetry Toolbox (BRAT, 2017). Retracking algorithm was applied to retrieve water level as leading edge of target return waveform deviates from on-board altimeter tracking gate (ESA & CNES, 2018). In this study, we used 'Off center of gravity retracker (ice-1)' retracking algorithm to retrieve water level (Wingham et al. 1986). The advantage of this algorithm is that if the return power of leading and trailing edge is in the analysis window, it can compute the midpoint of the leading edge for every waveform (Dubey, 2015).

Water level retrieved using altimeter data requires number of range and geophysical corrections to account for time delay of microwave pulses due to atmospheric effects, such as dry tropospheric correction, wet tropospheric correction, ionospheric correction and correction for pole and solid tidal effects on the Earth (Chelton et al. ,2001;Wahr,1985; Cartwright and Edden,1973). To estimate the water level, first of all we need the altitude of satellite orbit (Alt) and altimeter range value (R). Later, we apply geophysical and atmospheric corrections on retracked range values. The orthometric height (here, water surface elevation) is obtained by subtracting mean seas surface elevation with respect to reference ellipsoid WGS 84 ellipsoid (equation 1). Thus, it has to be noted that satellite altimetry water level records in this study are referenced to EGM 96 geoid.

$$H = Alt - R - [D_{tc} + W_{tc} + I_{onc} + S_{tc} + P_{tc}] - MSS_{ht} \qquad (1)$$

Where H: corrected orthometric height; Alt: the satellite altitude from reference ellipsoid; R: the satellite range; D_{tc}: the dry tropospheric correction; W_{tc}: the wet tropospheric correction; I_{onc}: the ionospheric correction; S_{tc}: the solid tide; P_{tc}: the pole tide correction; and MSS_{ht}: the mean sea surface from the reference ellipsoid.

Water level time series retrieved at the four virtual stations located between Tezpur and Guwahati were used for multi-site validation of the HD model, as well as for the validation of the RCs constructed with the model at the virtual stations.

4 Results and Discussion

Results and discussion section is divided into two parts: (1) Calibration and validation of HD model; (2) Significance of altimeter based water level and hydrodynamic model simulations; results of these activities are presented and discussed.

4.1 Calibration and validation of HD model

The HD model was calibrated for the period that goes from1st January 2013 to10th October 2013 (daily data) and validated for the time span going from 1st January 2014 to 6th March 2014 using water level data procured from IWAI, Guwahati. Manning's coefficient (*n*) controls the resistance of various LULC classes in the study domain, while cross-sections geometry controls the conveyance impacting the estimation of discharge and water level. To calibrate the HD model *n* was considered as the only parameter. Being the modelled river stretch very long and to make the calibration process trackable, *n* values of the different classes (settlement area, forest, agriculture area) falling in floodplain were kept constant. The channel *n* value was varied between the range 0.02-0.05 m $^{-1/3}$ s until we observed a good match between simulated and observed water level at Guwahati (Subramanya, 2014; Horrit & Bates, 2002; Chow, 1959). The Nash Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) were the statistical indexes considered for performance evaluation during calibration and validation phases.

The optimal Manning's *n* value for the river channel was found to be 0.04 m $^{-1/3}$ s (after datum correction of 2.8 m applied to observed water), for which the best agreement between simulated and observed water level was observed. The simulated water level is referenced to EGM96 geoid, while in-situ water level is reference to local datum i.e. mean sea level of India. The datum correction applied to the in-situ data in the present study is in agreement with the datum correction at Guwahati (3.09 m), as suggested by Dubey et al.(2014) based on the average deviation between in-situ and altimetry-derived water level records over a period of 10 years.

Figure 5 shows that there is a good match between simulated and observed water level during calibration (NSE 0.93; RMSE 0.31 m) and validation (NSE 0.79; RMSE 0.1 m). Woldemichael et al.(2010) investigated the role of Manning's roughness coefficient for the estimation of discharge in Brahmaputra River (Bangladesh region). They found that Manning's n of 0.04 m$^{-1/3}$s gave accurate estimates of discharge, confirming the calibration performed in this study. A value of 0.04m$^{-1/3}$smight appear too high for the silty sand of the Brahmaputra River, however, this may be due to the limitation in representing the braided channel geometry. The calculation of the hydraulic information (i.e., wetted area and perimeter, hydraulic radius, etc.) of multiple channels in braided river depends on how carefully channel-floodplain sub-sections have been provided as input data compared to the actual flow data. These difficulties prevail while tuning the calibration parameter and can affect model output.

Figure 5. Calibration and validation of the HD model at Guwahati station

4.2 Significance of altimeter based water level and hydrodynamic model simulations

Number of SARAL/AltiKa tracks passing over Brahmaputra River provides an opportunity to study the water level dynamics at finer intervals in addition to the existing gauging stations. Single value of water level was chosen among group of values that fall within the main channel along the track.

Rating curves were built at the virtual stations using HD modelling (Figure 6). Later, simulated water levels at virtual stations were compared with those retrieved from the altimeter. Statistics showed good correlation with NSE of 0.98 and RMSE of 0.15 m for track 352 near Kania Tapu (Figure 7).Statistics of the comparison between satellite altimetry and simulated water levels for all the virtual stations are given in Table 3.However, bias correction was applied to the altimetry derived water levels records ranging between 0.72 to 0.95 m before comparing with the modelled water levels.

The HD model was found to be stable in accordance with altimeter-based water levels. As the HD model was already calibrated using in-situ data at Guwahati (section 4.1), the comparison at virtual station not only leads to the multi-site validation of the HD model but also validation of the RCs obtained with it. To assess the extreme flood event discharge, validation of rating curves plays an important role. Lange et al., 2010 validated the HD model based rating curves using limited flood marks, while satellite altimetry provides spatio-temporal water level records at regular intervals.

The HD model simulations produce RC at each cross-section. The reliability of the constructed RCs for sparsely gauged rivers cannot be tested if we do not have observations.

In this case study, calibrated HD model using in-situ data and the availability of altimetry data enabled an option to verify the constructed RCs. It has to be noted that a merely comparison of water levelsdoes not give us the certainty that the estimated RCs are valid. However, if the model is calibrated (meaning that it reproduces the discharge correctly at the gauging stations) and the water levels simulated at the virtual stations are in line with satellite observations, we can reasonably assume that discharge-water relationships can be somehow reproduced by the model itself, and thus have some trust on the estimated RCs.

The construction of RCs at virtual stations allows expanding gauging network along the river. As there is synergy between altimetry and HD model simulated water level, RCs can be used to estimate the discharge at virtual stations and to estimate the contribution of different lateral tributaries along the main river.

RC is a cost effective and quick tool to estimate discharge using water level data. Rigours studies have been carried out to extrapolate rating curves using curve fitted to the water level and discharge time series (Paris et al., 2016; Dubey et al., 2014). Inconsistencies can be observed during estimation of discharge using power model based rating curves for extreme flood events beyond exploited hydrometric data. However, HD model framework can address such extreme flood events by taking into account the hydraulic information around the gauging station. More literature can be found on extrapolation of rating curves using HD modelling and related uncertainties (Di Baldassare & Montanari, 2009; Reitan & Petersen-Overleir, 2009; Naulet et al., 2005).

Figure 6. Rating curves generated at virtual stations by means of the HD model run over the period from 1st January 2013 to 10th October 2013

Figure 7. Comparison of the water level provided by the altimeter and the HD model (Track 352)

5 Limitations of the study

The proposed study consists of certain limitations based on the availability and accuracy of the data and study domain. The 1D numerical scheme was applied to the braided Brahmaputra River and floodplains by extending channel cross-sections. Assuming one dimensionality of the flow limits lateral propagation, which is very important especially in braided rivers. The contribution of the tributaries was estimated using drainage-area ratio method. Reliability of discharge estimation using RC depends on the accuracy of surveyed river data and DEM used for river cross-sections, as well as on their capability to monitor the geomorphological evolution of the area (i.e., topographic data need to be updated in time). The application of 2D or 1D-2D coupled model using denser surveyed river cross-sections can be a future study.

The selection of the altimeter dataset (SARAL/AltiKa) was done based on the location of the altimeter measurements that fall within the available hydrometric and topographic data. The same methodology can be explored considering Jason 3 and Sentinel 3 data, as well as those of the upcoming SWOT mission (Biancamaria et al., 2016).

6 Conclusions

This study investigates the advantages of altimeter measurements in combination with HD model in a sparsely gauged river stretch of the Brahmaputra River, India. Water level series was retrieved at 4 tracks of SARAL/AltiKa along the river stretch included within the two gauging stations at Tezpur and Guwahati.

The study combined HD model with satellite derived water levels showing the potential of those latter to enable a multi-site validation of the numerical model, as well as the construction of additional RCs. The RCs produced at virtual stations allows the expansion of the gauging network along the Brahmaputra River and the estimation of the discharge at these locations, which may imply the possibility to infer the contribution of the several tributaries that flow into the main river.

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Tables

Table 1. Summary of boundary conditions

Location	Boundary Conditions Type	Data
Tezpur (u/s)	Open	Water Level
Tributaries	Point Source	Water Level
Guwahati (d/s)	Rating curve	Water Level-Discharge

Table 2. Contribution of the tributaries

Tributary	Catchment area (sq. km)	Contribution in % using drainage-area ratio method
RT1	1307.33	0.32
RT2	2640.97	0.64
RT3	1618.78	0.39
RT4	266.43	0.06
LT1	21740.11	5.24

Table 3. Statistics of the comparison between satellite altimetry water level and modelled water level

Virtual Stations	RMSE (m)	NSE	Bias Correction (m)
Track 352	0.15	0.98	0.72
Track 623	0.42	0.89	0.95
Track 165	0.36	0.92	0.78
Track 896	0.27	0.94	0.83

Figure

Figures

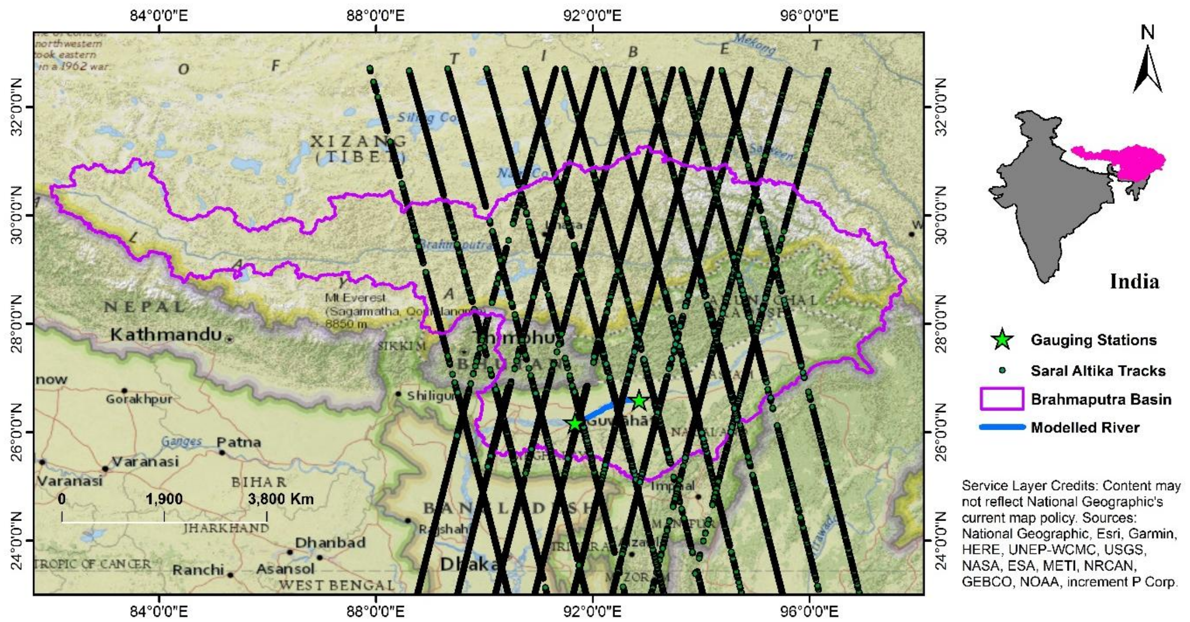

Figure 1. Overview of study area and modelled river reach

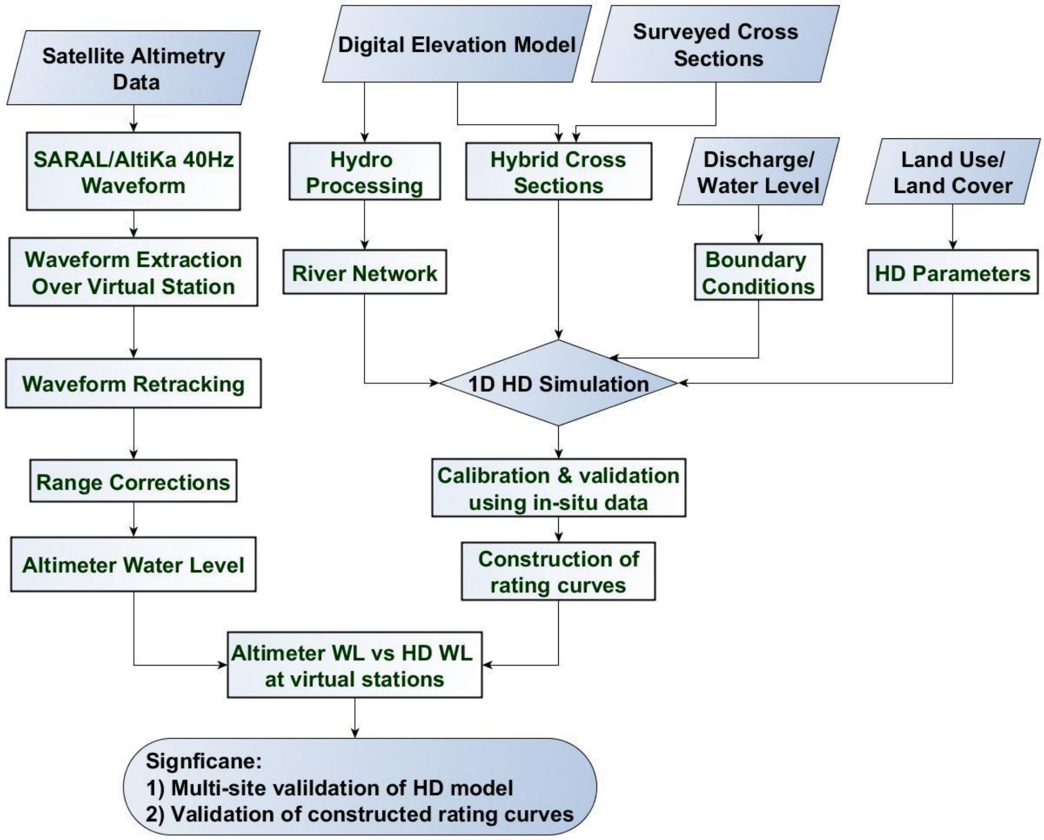

Figure 2. Overall methodology adopted in the study

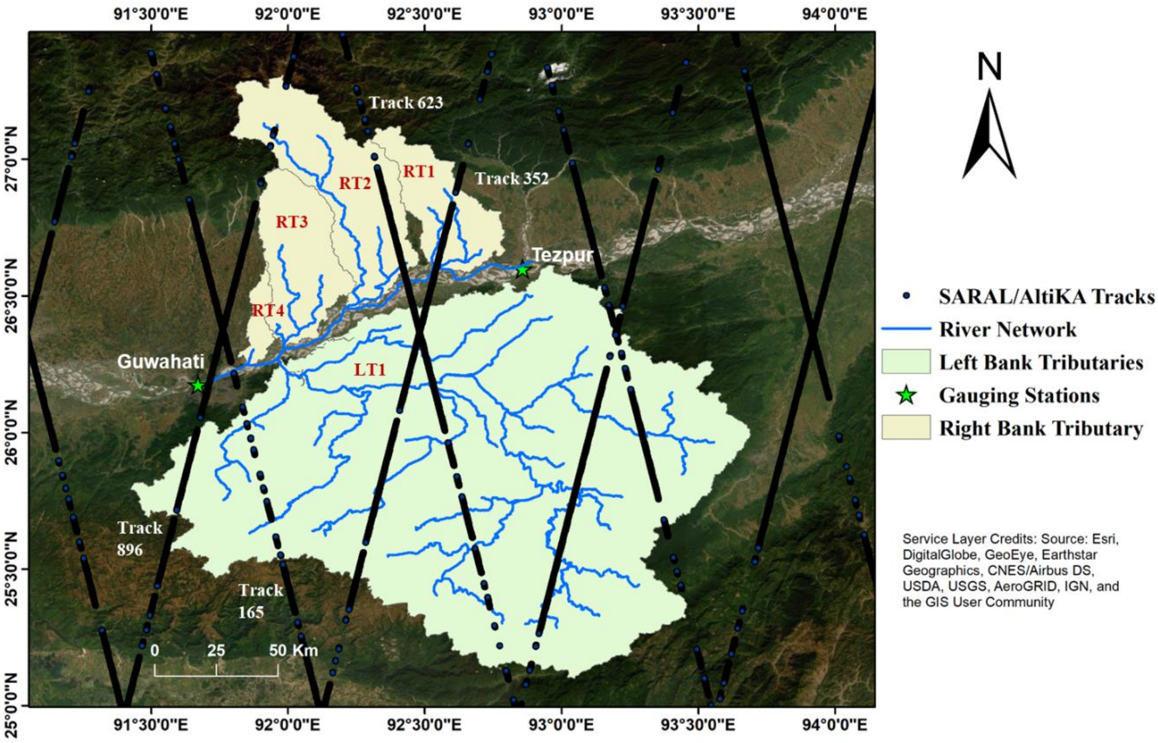

Figure 3. Brahmaputra River reach for HD model and SARAL/Altika tracks crossing the river

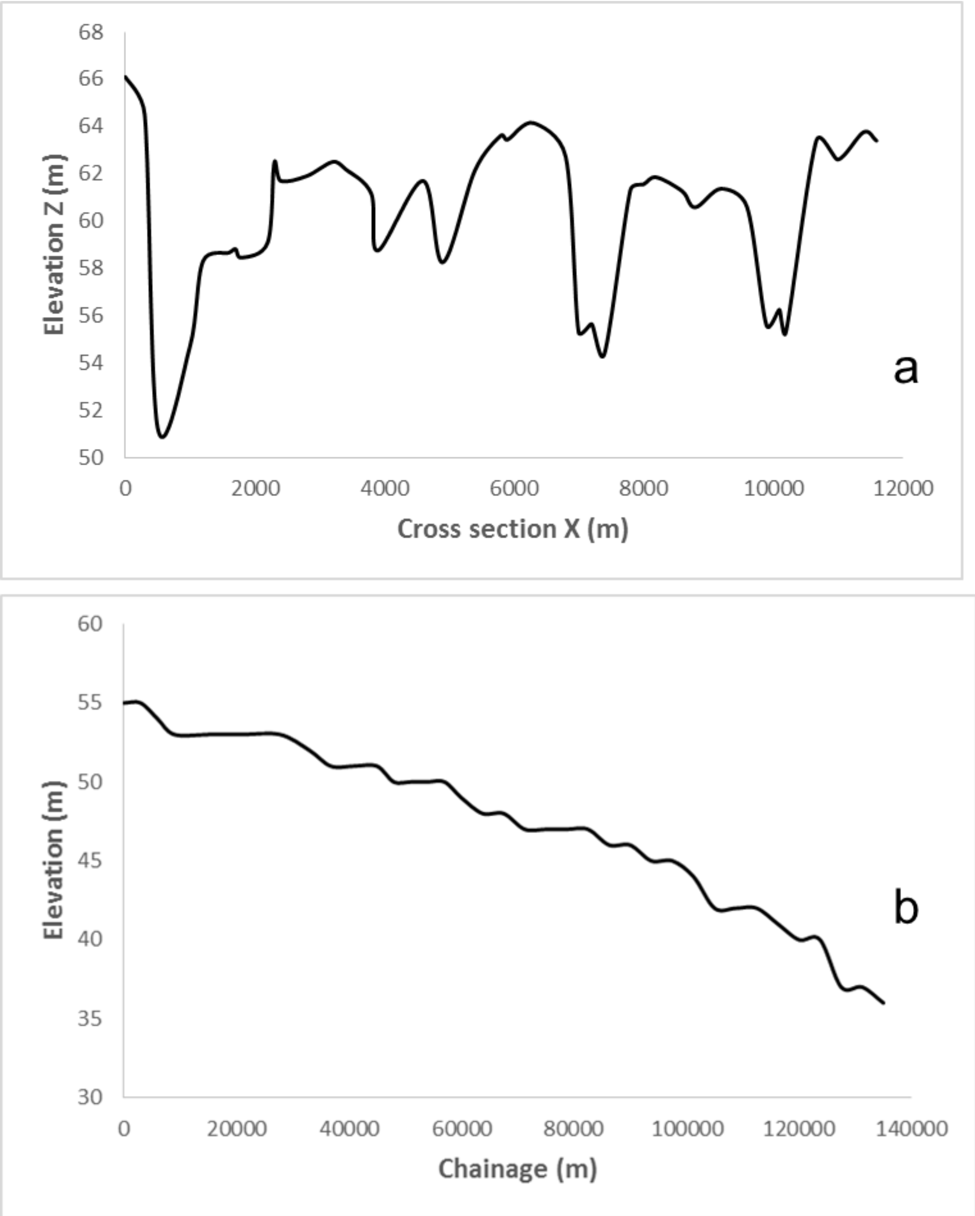

Figure 4. (a) Hybrid cross section at 23000 m chainage (b) Longitudinal profile of the main channel

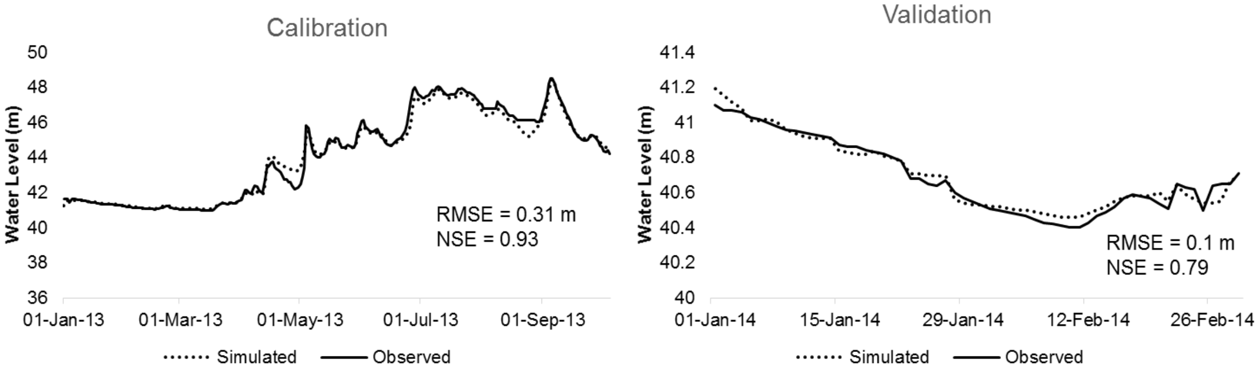

Figure 5. Calibration and validation of the HD model at Guwahati station

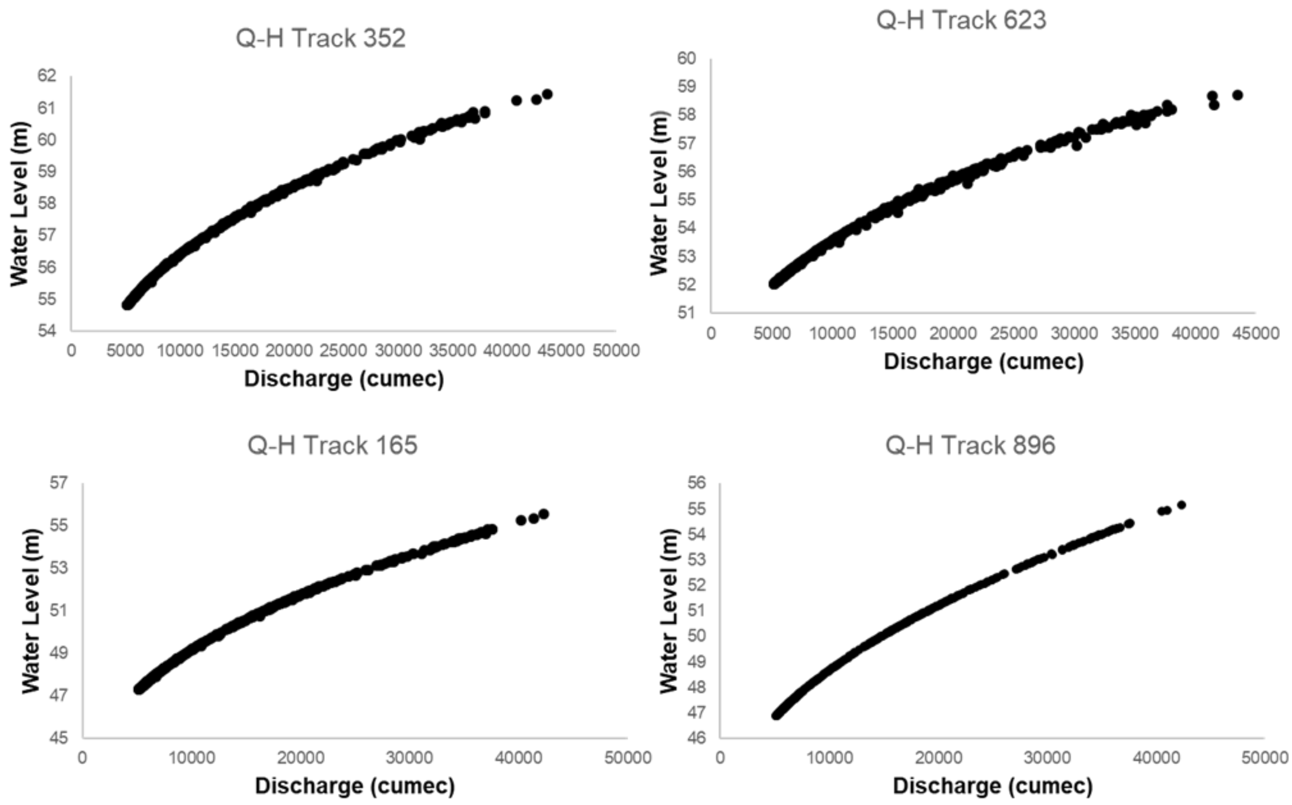

Figure 6. Rating curves generated at virtual stations by means of the HD model run over the period from 1st January 2013 to 10th October 2013

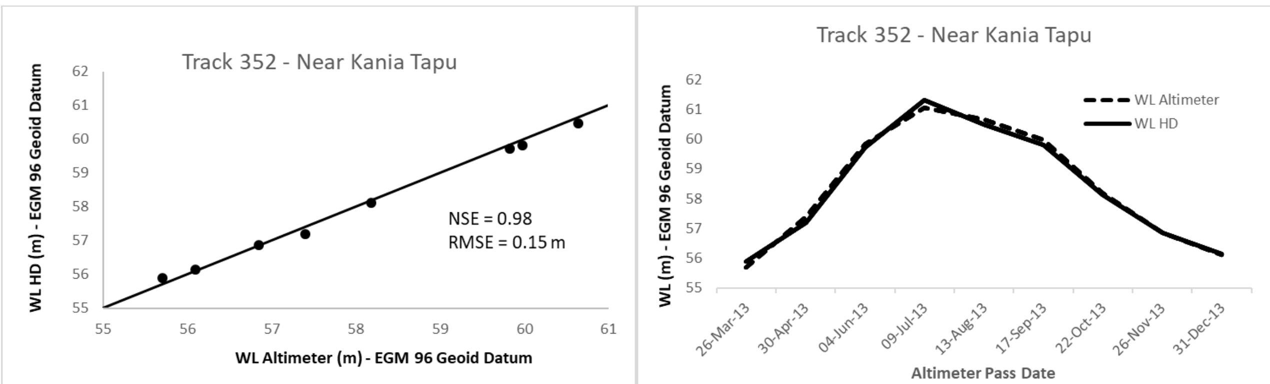

Figure 7. Comparison of the water level provided by the altimeter and the HD model (Track 352)